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SIPEX 2012: Extreme sea-ice and atmospheric conditions off East Antarctica

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ABSTRACT

In 2012, Antarctic sea-ice coverage was marked by weak annual-mean climate anomalies that consisted of opposing anomalies early and late in the year (some setting new records) which were interspersed by near-average conditions for most of the austral autumn and winter. Here, we investigate the ocean-ice-atmosphere system off East Antarctica, prior to and during the Sea Ice Physics and Ecosystems eXperiment [SIPEX] 2012, by exploring relationships between atmospheric and oceanic forcing together with the sea-ice and snow characteristics. During August and September 2012, just prior to SIPEX 2012, atmospheric circulation over the Southern Ocean was near-average, setting up the ocean-ice-atmosphere system for near-average conditions. However, below-average surface pressure and temperature as well as strengthened circumpolar winds prevailed during June and July 2012. This led to a new record (19.48×10^6 km^2) in maximum Antarctic sea-ice extent recorded in late September. In contrast to the weak circum-Antarctic conditions, the East Antarctic sector (including the SIPEX 2012 region) experienced positive sea-ice extent and concentration anomalies during most of 2012, coincident with negative atmospheric pressure and sea-surface temperature anomalies. Heavily deformed sea ice appeared to be associated with intensified wind stress due to increased cyclonicity as well as an increased influx of sea ice from the east. This increased westward ice flux is likely linked to the break-up of nearly 80% of the Mertz Glacier Tongue in 2010, which strongly modified the coastal configuration and hence the width of the westward coastal current. Combined with favourable atmospheric conditions the associated changed coastal configuration allowed more sea ice to remain within the coastal current at the expense of a reduced northward flow in the region around 141°–145°E. In addition a westward propagating positive anomaly of sea-ice extent from the western Ross Sea during austral winter 2012 has been identified to have fed into the westward current of the SIPEX 2012 region. A pair of large grounded icebergs appears to have modified the local stress state as well as the structure of the ice pack upstream and also towards the Dalton Glacier Tongue. Together with the increased influx of sea ice into the regions, this contributed to the difficulties in navigating the SIPEX 2012 region.

1. Introduction

In recent decades, sea ice in both polar regions has undergone significant yet contrasting change overall (although there are regional similarities (Stammerjohn et al., (2012)). In the Arctic, the loss of overall sea-ice extent in summer has accelerated to about 13% per decade relative to the 1981–2010 average (NASA, 2016) accompanied by substantial loss of multi-year ice (Kwok, 2007; Maslanik et al., 2011), leading to thinning of the sea-ice pack (e.g., Lindsay and Schweiger (2015)). These dramatic changes, which have been attributed to a complex combination of both thermodynamic and dynamic processes and associated feedbacks, have led to a less robust sea-ice cover that is more vulnerable to dynamic and thermodynamic forcing (Overland et al., 2012; Perovich, 2011; Rampal et al., 2009). At the same time, the overall Antarctic sea-ice extent has exhibited a statistically significant (albeit weak) increasing trend of +1.5% per decade for 1980–2014 (Turner et al., 2015), but composed of high regional and seasonal variability (Holland, 2014; Turner et al., 2015). Most outstanding are the sustained loss of sea ice in the Amundsen–Bellingshausen seas (−6.8% per decade) and increasing sea-ice extent in the Ross

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Sea (+4.9% per decade) (Turner et al., 2015). Both coincide with similar sign regional changes in annual duration of the sea-ice cover, i.e., shortening of the sea-ice season by over 3 months in the Amundsen–Bellingshausen seas sector and lengthening by ~2.6 months in the western Ross Sea (Stammerjohn et al., 2012). Most recently, and after successive ice-extent maxima from 2012 to 2014 (Reid and Massom, 2015), the 2015 maximum ice extent was close to the long-term average, possibly associated with the return of a well developed El Niño. Consequently, higher surface pressure and warmer surface air and sea-surface temperatures around the Western Antarctic may have been responsible for driving down the overall Antarctic sea-ice extent. In East Antarctica, the focus of this study, the patterns of change in sea-ice annual advance, retreat and duration are more complex, with regions of shortening and lengthening trends in sea-ice annual duration (of ±2–3 days/year) in juxtaposition (Massom et al., 2013b). It is worth noting that for the East Antarctic there is no consistent response of sea-ice distribution to changing El Niño conditions (Stammerjohn et al., 2008).

The causes of the overall Antarctic sea-ice increase, and the regionally- and seasonally-contrasting contributions, are poorly understood, although a number of mechanisms have been proposed (Hobbs et al., 2016). Holland and Kwok (2012) suggest that wind-driven changes in ice transport and thermodynamics are the dominant drivers of ice-concentration trends off West Antarctica and all other Antarctic sea-ice regions, respectively. Other mechanisms proposed include: enhanced recent freshening and stabilisation of the ocean surface mixed layer (Bintanja et al., 2013) by accelerated basal melt of Antarctic ice shelves (Pritchard et al., 2012); increased precipitation (Liu and Curry, 2010); seasonal thermal ocean-ice feedback (Stammerjohn et al., 2012); and feedback between changes in the high-latitude Southern Ocean and atmosphere (Zhang et al., 2007). Current lack of consensus as to what is driving observed patterns of Antarctic sea-ice change and variability underlines the complexity of the Antarctic air-sea-ice interaction system set against a lack of observations. It also points to the urgent need for improved understanding of the processes involved and how they are changing around Antarctica. This is, in turn, a key prerequisite to improving climate-model performance and predictive capability (Turner et al., 2015). Particularly important in this regard is treatment of sea-ice seasonality as well as extent, concentration and thickness.

An impediment to our understanding of how and why Antarctic sea ice is changing, and our confidence in model projections of its future response, is that (compared to the Arctic) there are few sea-ice and snow-cover thickness observations for the Southern Hemisphere (Maksym et al., 2012). Current knowledge is largely limited to *in situ* and ship-based datasets that are limited in both space and time (e.g., Heil, 2006; Massom et al., 2001; Ozsoy-Cicek et al., 2011; Worby et al., 2008). This issue is exacerbated by the difficulty of obtaining accurate large-scale thickness information from satellites in Antarctica. Compared to the Arctic, Antarctic sea ice is characterised by near-zero freeboard and extensive surface flooding (Maksym and Markus, 2008) that significantly increase the difficulty of deriving ice thickness from satellite altimetry (Kern and Spreen, 2015; Lubin and Massom, 2006). Moreover, techniques using radar altimetry require independent information on snow thickness and density, and lack of information on spatio-temporal variability in these quantities contributes to current large uncertainty in derived ice-thickness estimates. As a result of these factors, few satellite-derived ice-thickness datasets are available (i.e., Xie et al., 2013; Zwally et al., 2008), and they remain largely unvalidated.

As background, sea-ice coverage in this sector of East Antarctica is strongly seasonal and occupies a relatively narrow zone that extends from the coast (at about 66°–67°S – relatively far north) to about 60°–62°S at maximum extent (Gloersen et al., 1992; Massom et al., 2013b). As shown by Massom et al. (2013b, Fig. 1), the climatological patterns of annual advance, retreat and duration of the sea-ice pack in this sector of East Antarctica largely mirror the broad-scale ocean bathymetry, with increased meridional extent to the immediate west of the SIPEX 2012 region. Regional oceanic circulation and thus patterns of sea-ice drift, both within and into/out of the region, are dominated by the eastward-flowing Antarctic Circumpolar Current [ACC] to the north and the westward-flowing Antarctic Coastal Current or East Wind Drift that skirts the continental margin to the south (Heil and Allison, 1999). These two major current regimes are separated by the Antarctic Divergence, with meridional pathways (mainly northward retroflections) in ice drift occurring near 110°, 125° or 135°E (Heil and Allison, 1999). While the Antarctic Divergence itself undergoes a seasonal north-south relocation (Heil and Allison, 1999), the relative latitude of the ice edge to that of the Antarctic Divergence provides feedback into the northward expansion of the sea-ice cover. During low ice extent in summer to mid autumn, the northern ice edge remains well south of the Antarctic Divergence, and hence the zonal ice transport is solely to the west, with the mean zonal deviations largely depending on barotropic ocean currents. As the ice edge advances northward of the Antarctic Divergence, ice in the eastward flow experiences a slight northward deflection due to Coriolis forcing, which provides a positive feedback to the equatorward expansion of the ice pack.

While narrow (about 550–700 km) and with large interannual variability, the sea-ice zone in the region of interest is highly dynamic, with transient storms driving strong ice deformation and precipitation events – causing considerable spread in the sea-ice and snow-cover thickness distributions (Heil and Allison, 1999; Toyota et al., 2016). Moreover, the sea ice comprises a number of distinct zones with different morphological characteristics (Massom and Stammerjohn, 2010). These are (from north to south): (i) the highly-dynamic marginal ice zone where sea-ice characteristics and processes are strongly affected by wave-ice interaction; (ii) the inner pack, characterised by larger floes and thicker snow cover; and (iii) the near-coastal and coastal zones, which are strongly affected by interaction with the ice-sheet margins and icebergs that ground in waters shallower than ~450 m. The latter element also comprises polynyas and fast ice, including an area of fast ice in the embayment to the west of the Dalton Iceberg Tongue that regularly breaks out to feed ice into the coastal current (Heil et al., 2011). SIPEX 2012 largely sampled ice from the inner and near-coastal zones.

Here, we analyse new information on the ocean-sea ice-snow-atmosphere system off East Antarctica acquired during SIPEX 2012. This study was conducted on the icebreaker RSV *Aurora Australis* in the late winter-early spring of 2012 (22 September to 11 November) off the Wilkes Land coast and in the region bounded by 63°–66°S and 117°–121°E. This region was also the focus of two previous experiments i.e., ARISE in 2003 (Massom et al., 2006) and SIPEX 2007 (Worby et al., 2011), enabling direct comparison of sea-ice conditions in those years. Details of the experimental sites for SIPEX 2012 are given in Meiners et al. (2016, Fig. 1), while Toyota et al. (2016) provide a detailed analysis of the coincident snow conditions. An overriding feature of SIPEX 2012 is the apparent extremity of ice conditions compared to previous years sampled, with a predominance of thick and heavily-deformed first-year ice (with maximum thicknesses peaking around 15 m (Williams et al., 2015)). The snow cover was also unusual, in that its average depth of 0.45 m was almost three times that observed in the region between 1992 and 2007 (Toyota et al., 2016). Here, we combine *in situ*, satellite, meteorological and other data to investigate how local and regional ocean-ice-atmosphere interactions (including icebergs) shaped the sea-ice conditions encountered prior to and during